# CHAPTER 21: ELECTRIC CHARGE

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## تسريحة الموسم!!!

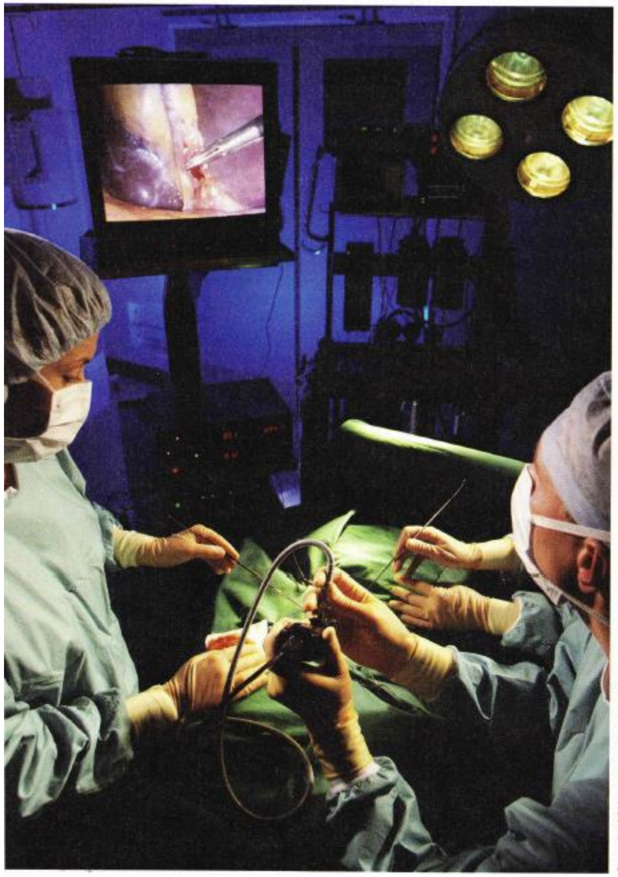
بدون جل... بدون بخاخ مثبت...

فقط قليل من الشحنات الكهربية الساكنة ☺

# What we will learn

- Properties of electric charge
- Electrical properties of materials
- Coulomb’s law: Electrostatic Force

# Electric Charge



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*Hospital personnel go to extraordinary lengths to avoid bacterial infection of a patient. Surfaces are scrubbed, masks are donned, hands are meticulously cleaned and then gloved, and instruments are sanitized at high temperature and in alcohol baths. But there are still subtle sources of bacteria, such as possibly in this photograph.*

**Can you find the bacterial source?**

The answer is in this chapter.

# Electric Charge

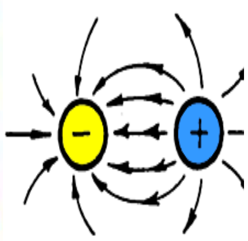
Greek
E(rubbing)
M (rocks)

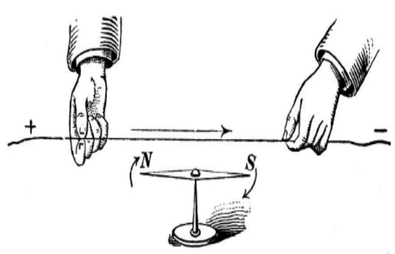
1750
Benjamin Franklin

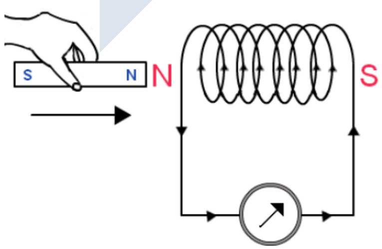
1820
Oersted
E&M
Compass deflection

Faraday

Maxwell
Mathematical Formulation




$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

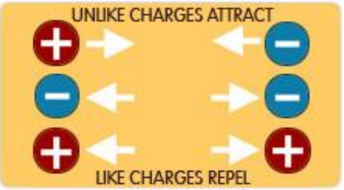
$$\nabla \cdot \mathbf{B} = 0$$

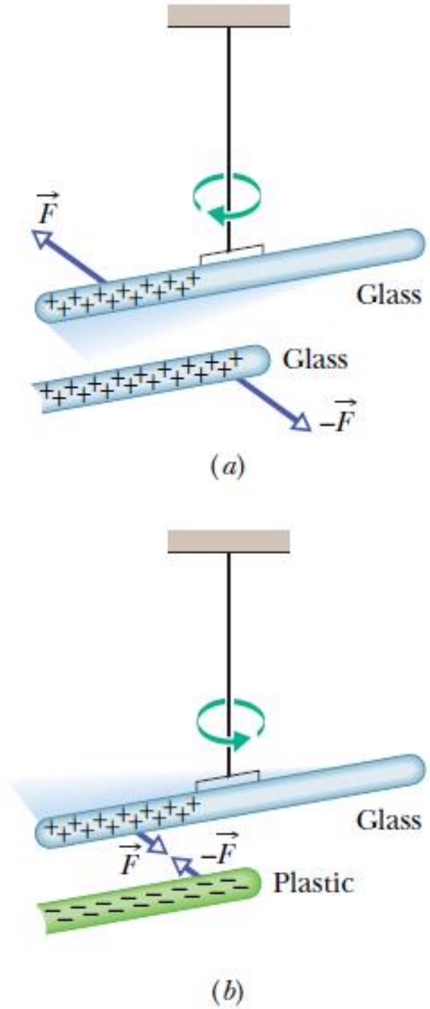
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

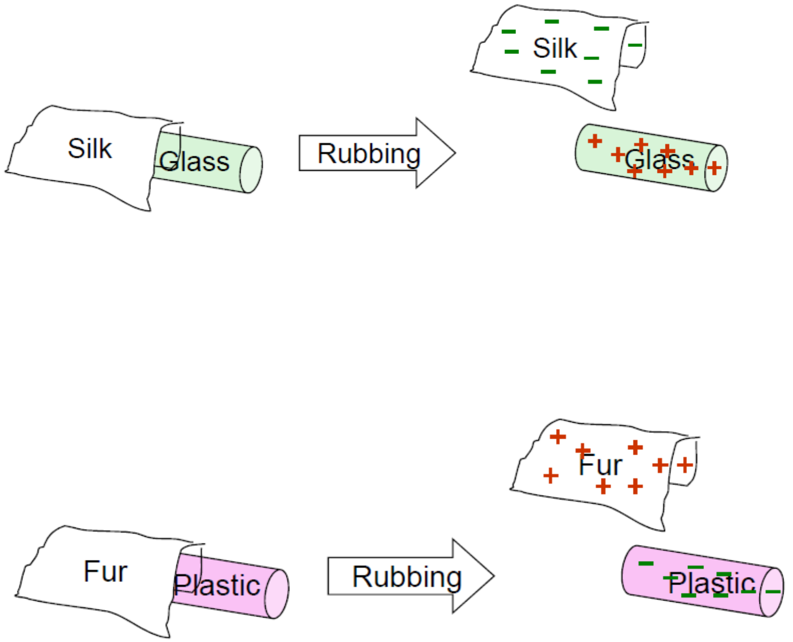
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

# Electric Charge

Charge with the same electric sign repel each other, and charge with opposite electric sign attract each other.



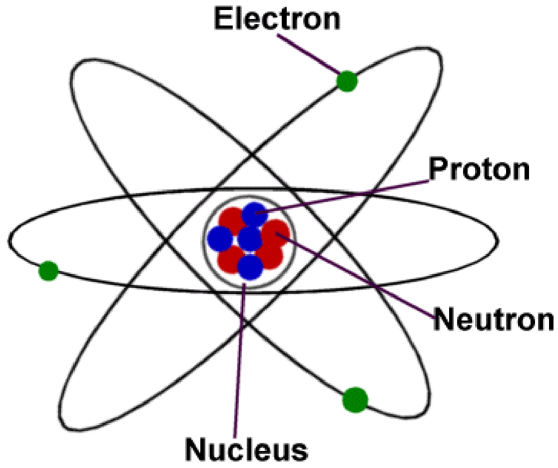



# Electric Charge

Atoms consist of positively charged *protons*, negatively charged *electrons*, and electrically neutral *neutrons*. The protons and neutrons are packed tightly together in a central nucleus.

Electric Charge is an intrinsic characteristic of the fundamental particles making up those objects



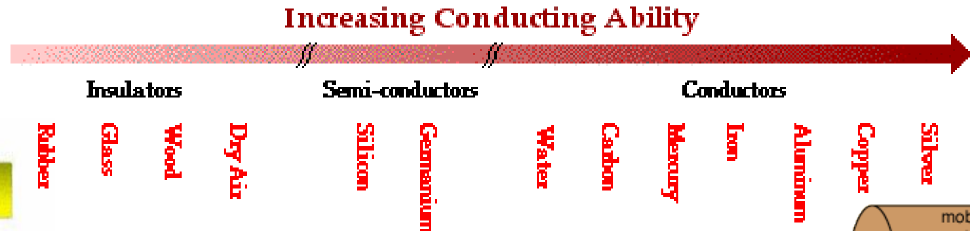
# Conductors and Insulators

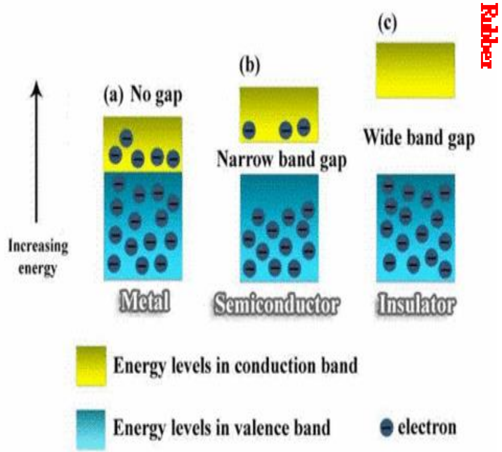
### Insulators
- Charge can't move freely
- Rubber, plastic, glass

### semiconductor
- Between conductors and insulators
- Silicon & germanium

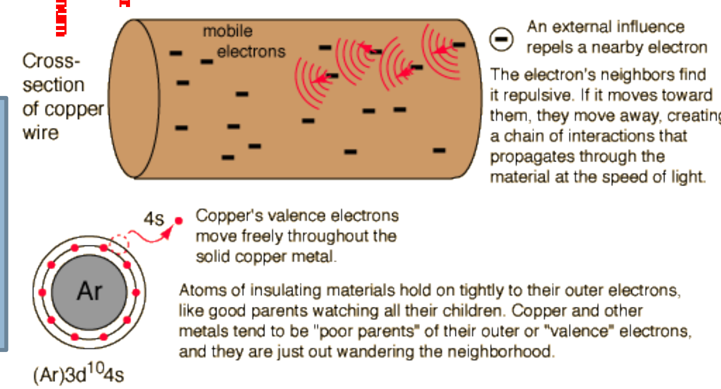
### Conductors
- Charge move freely
- Metals, human body, water

### Super conductor
- Perfect conductor with no hindrance




The properties of conductors and insulators are due to the structure and electrical nature of atoms



# Electric Charge

## Characteristics of electric charge

- Type (+,-)
- Attraction and repulsion

- Conserved
- Not created only transferred

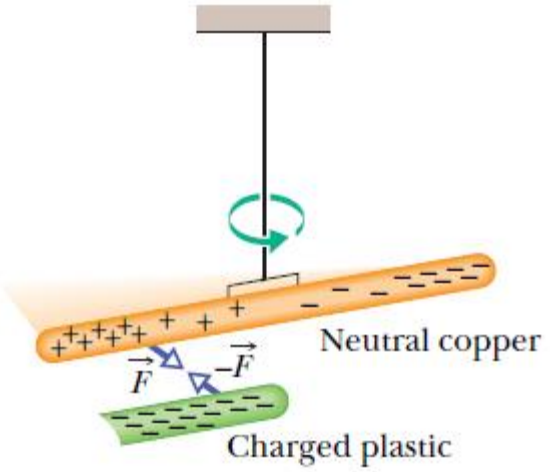
- Quantized Q=ne
- Discrete not continuous

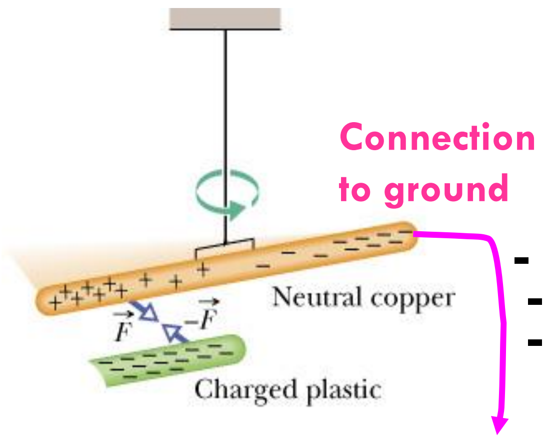
$$^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{Th} + {}^{4}\mathrm{He},$$

$$e = 1.602 \times 10^{-19}\ \mathrm{C}.$$

$$n = \pm 1, \pm 2, \pm 3, \ldots,$$

# Conductors and Insulators




Charged by induction

**Grounding:**

Connecting conductors through the earth.

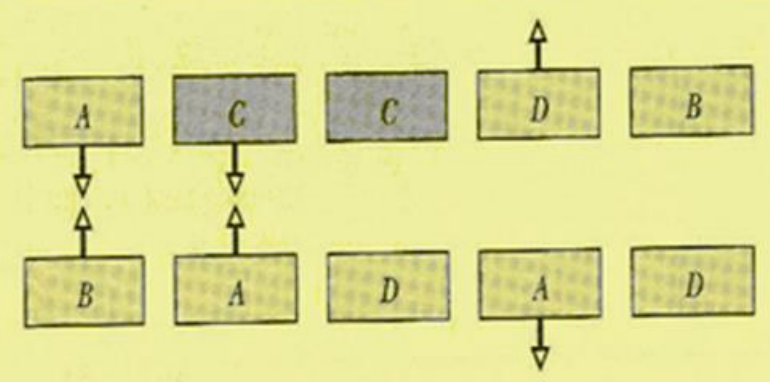
→ Charged conductors become neutral

→ Discharging a conductor

Only negative charges move, positive ions are fixed.

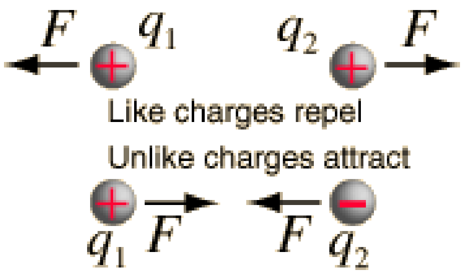
# Conductors and Insulators

**CHECKPOINT 1** The figure shows five pairs of plates: $A$, $B$, and $D$ are charged plastic plates and $C$ is an electrically neutral copper plate. The electrostatic forces between the pairs of plates are shown for three of the pairs. For the remaining two pairs, do the plates repel or attract each other?



# Coulomb's Law

- If two charged particles are brought near each other they exert a force on each other.
- Coulomb's force or electrostatic force
- Force either attraction or repulsion




- Force is a vector quantity (line between the two particles)
- Follows the inverse square law (like gravitational force)

$k_e = 8.9875 \times 10^9\ \mathrm{N \cdot m^2/C^2}$

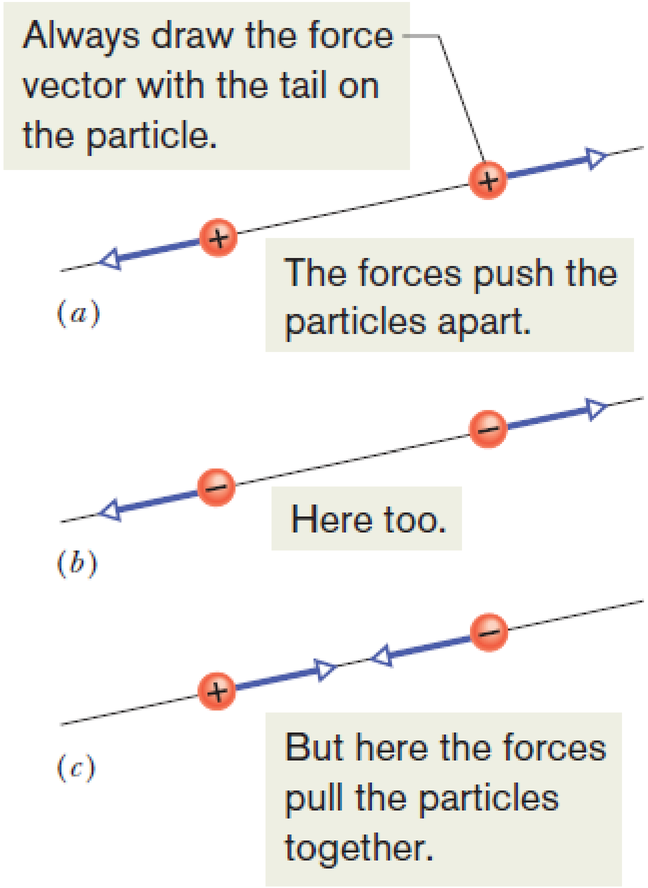
$k_e = 1/4\pi\varepsilon o$

$\varepsilon o = 8.8542 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$

$$F_e = k_e \frac{|q_1||q_2|}{r^2} \quad , \quad \mathbf{F}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}$$

The SI unit of charge is the ***coulomb.***

# Coulomb's Law

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The SI unit of charge is the ***coulomb.***

$$1\ \text{C} = (1\ \text{A})(1\ \text{s}).$$

$$i = \frac{dq}{dt} \qquad \text{(electric current),}$$

# Electrostatic and Gravitation Forces

| Electrostatic Force | Gravitational Force |
| --- | --- |
| $$\mathbf{F}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}$$ | $$\mathbf{F}_g = G \frac{m_1 m_2}{r^2} \hat{\mathbf{r}}$$ |
| + or – | Always positive |
| because there are two types of charge | because there are only one type of mass |

# Coulomb's Law & Superposition Principle

$$F_e = k_e \frac{|q_1||q_2|}{r^2} \quad , \quad \mathbf{F}_{12} = k_e \frac{q_1 q_2}{r^2} \hat{\mathbf{r}}$$

If there are *n* charged particles, they interact independently in pairs, and the force on any one of them, say particle 1, is given by the vector sum

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \vec{F}_{15} + \cdots + \vec{F}_{1n}$$

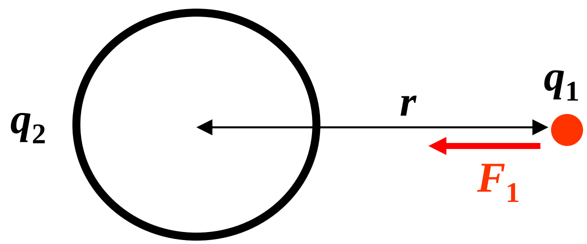
in which, $\mathbf{F}_{1,4}$ is the force acting on particle 1 due to the presence of particle 4, etc.

One must remember that $\vec{F}_{12}$ , $\vec{F}_{13}$ , ... are vectors and thus we must use vector addition.

# Coulomb's Law & Shell Theorem

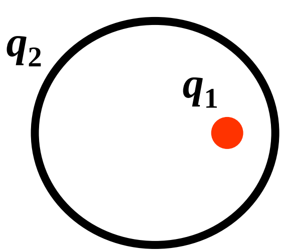
As with gravitational force law, the shell theorem has analogs in electrostatics:

- A shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell's charge were concentrated at its center.




If $q_1$ is outside the shell, then the force $F_1$ exerted by $q_2$ is $$F_1 = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{r^2}$$

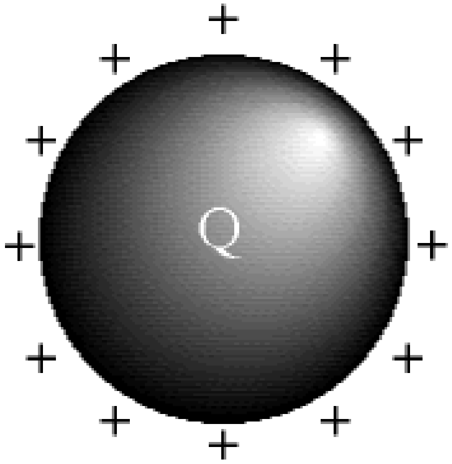
- If a charged particle is located inside a shell of uniform charge, there is no net electrostatic force on the particle from the shell.




If $q_1$ is inside the shell, then the force is $F_1 = 0$

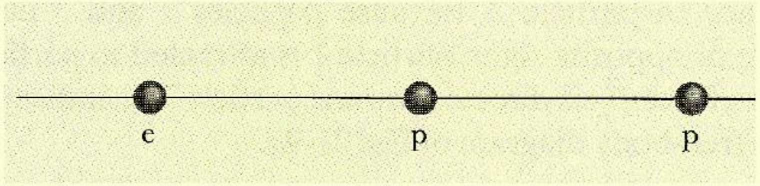
# Spherical Conductors

If excess charge is placed on a spherical shell that is made of conducting material, the excess charge spreads uniformly over the (external) surface.



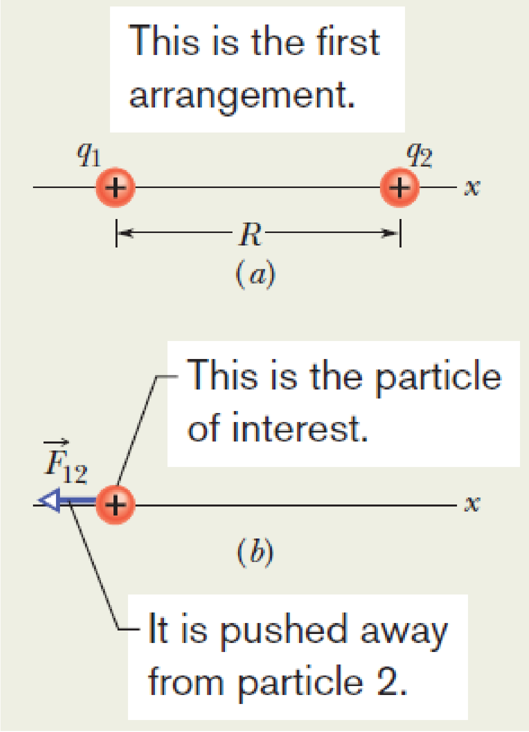
# Coulomb's Law

**CHECKPOINT 2** The figure shows two protons (symbol p) and one electron (symbol e) on an axis. What is the direction of (a) the electrostatic force on the central proton due to the electron, (b) the electrostatic force on the central proton due to the other proton, and (c) the net electrostatic force on the central proton?



# Coulomb's Law

(a) Figure 21-8*a* shows two positively charged particles fixed in place on an $x$ axis. The charges are $q_1 = 1.60 \times 10^{-19}$ C and $q_2 = 3.20 \times 10^{-19}$ C, and the particle separation is $R = 0.0200$ m. What are the magnitude and direction of the electrostatic force $\vec{F}_{12}$ on particle 1 from particle 2?



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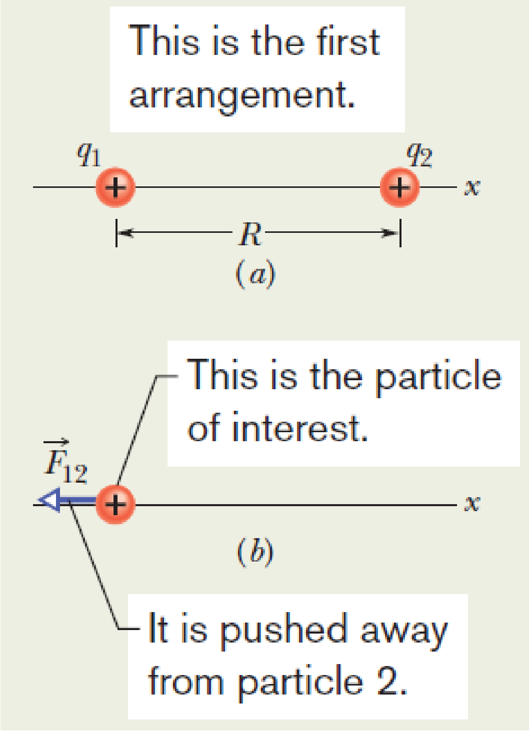



$$F_{12} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{R^2}$$

$$= (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2})$$

$$\times \frac{(1.60 \times 10^{-19}\ \mathrm{C})(3.20 \times 10^{-19}\ \mathrm{C})}{(0.0200\ \mathrm{m})^2}$$

$$= 1.15 \times 10^{-24}\ \mathrm{N}.$$

Thus, force $\vec{F}_{12}$ has the following magnitude and direction (relative to the positive direction of the $x$ axis):

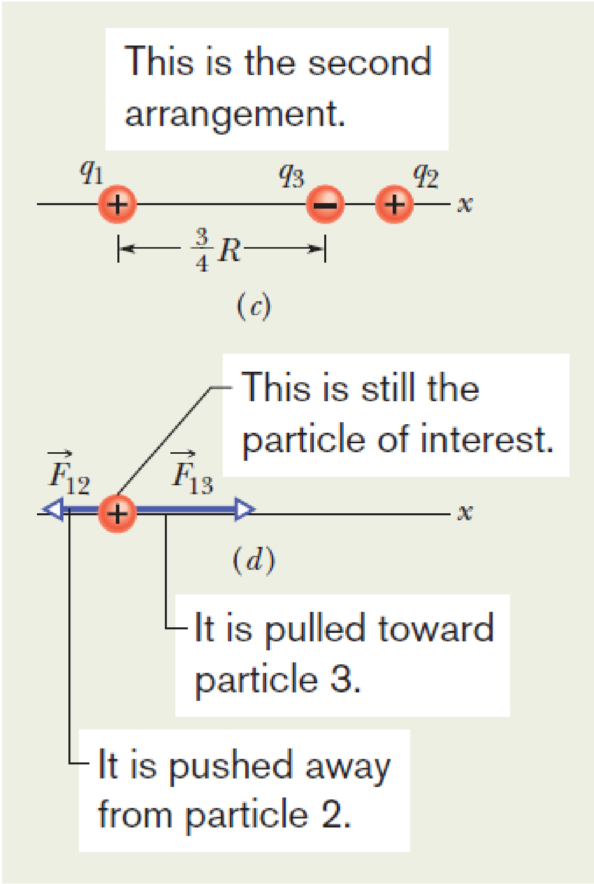
$$1.15 \times 10^{-24}\ \mathrm{N} \quad \text{and} \quad 180°. \qquad \text{(Answer)}$$

We can also write $\vec{F}_{12}$ in unit-vector notation as

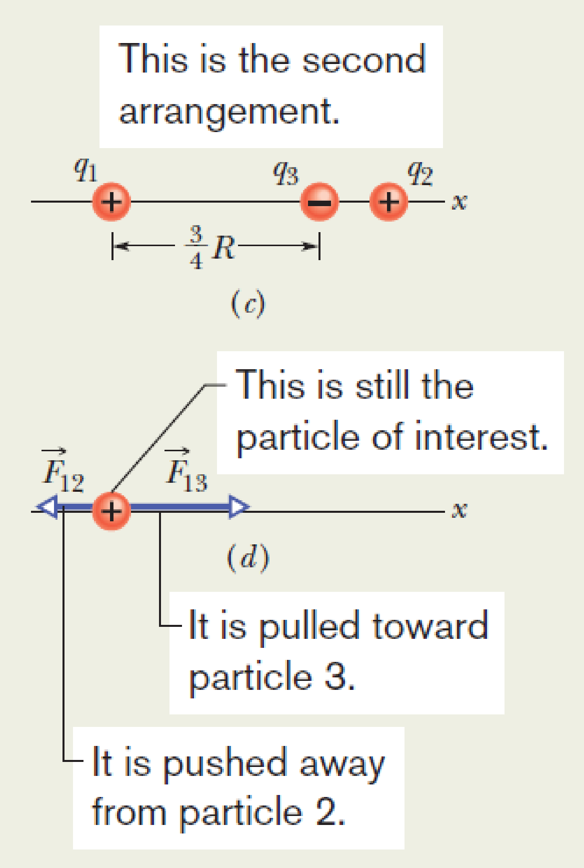
$$\vec{F}_{12} = -(1.15 \times 10^{-24}\ \mathrm{N})\hat{\mathrm{i}}. \qquad \text{(Answer)}$$

# Coulomb's Law

(b) Figure 21-8*c* is identical to Fig. 21-8*a* except that particle 3 now lies on the *x* axis between particles 1 and 2. Particle 3 has charge $q_3 = -3.20 \times 10^{-19}$ C and is at a distance $\frac{3}{4}R$ from particle 1. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 3?



# Coulomb's Law




$$F_{13} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_3|}{(\frac{3}{4}R)^2}$$

$$= (8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)$$

$$\times \frac{(1.60 \times 10^{-19}\ \text{C})(3.20 \times 10^{-19}\ \text{C})}{(\frac{3}{4})^2(0.0200\ \text{m})^2}$$

$$= 2.05 \times 10^{-24}\ \text{N}.$$

We can also write $\vec{F}_{13}$ in unit-vector notation:

$$\vec{F}_{13} = (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}.$$

The net force $\vec{F}_{1,\text{net}}$ on particle 1 is the vector sum of $\vec{F}_{12}$ and $\vec{F}_{13}$; that is, from Eq. 21-7, we can write the net force $\vec{F}_{1,\text{net}}$ on particle 1 in unit-vector notation as

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13}$$

$$= -(1.15 \times 10^{-24}\ \text{N})\hat{\text{i}} + (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}$$

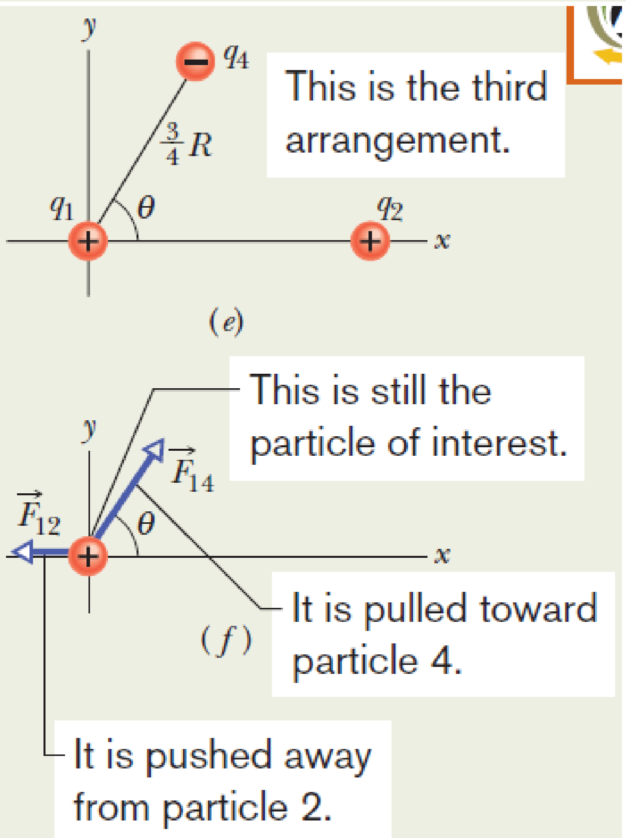
$$= (9.00 \times 10^{-25}\ \text{N})\hat{\text{i}}. \qquad \text{(Answer)}$$

Thus, $\vec{F}_{1,\text{net}}$ has the following magnitude and direction (relative to the positive direction of the $x$ axis):

$$9.00 \times 10^{-25}\ \text{N} \quad \text{and} \quad 0°. \qquad \text{(Answer)}$$

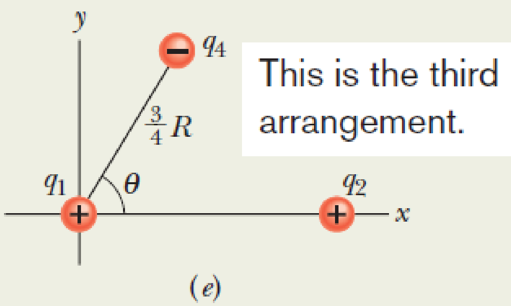
# Coulomb's Law

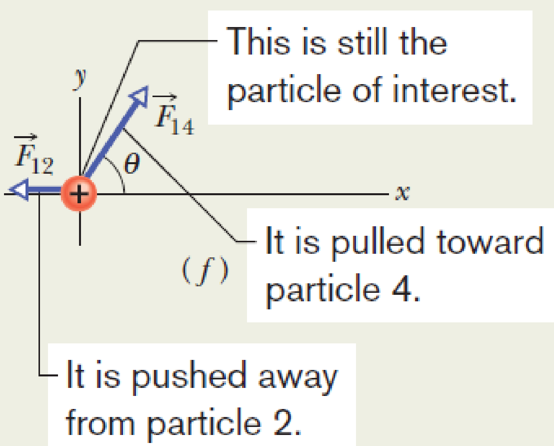
(c) Figure 21-8*e* is identical to Fig. 21-8*a* except that particle 4 is now included. It has charge $q_4 = -3.20 \times 10^{-19}$ C, is at a distance $\frac{3}{4}R$ from particle 1, and lies on a line that makes an angle $\theta = 60°$ with the $x$ axis. What is the net electrostatic force $\vec{F}_{1,\text{net}}$ on particle 1 due to particles 2 and 4?



# Coulomb's Law

$$F_{14} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_4|}{(\frac{3}{4}R)^2}$$
$$= (8.99 \times 10^9\ \mathrm{N\cdot m^2/C^2})$$
$$\times \frac{(1.60 \times 10^{-19}\ \mathrm{C})(3.20 \times 10^{-19}\ \mathrm{C})}{(\frac{3}{4})^2(0.0200\ \mathrm{m})^2}$$
$$= 2.05 \times 10^{-24}\ \mathrm{N}.$$




$$F_{1,\text{net},x} = F_{12,x} + F_{14,x} = F_{12} + F_{14}\cos 60^\circ$$
$$= -1.15 \times 10^{-24}\ \mathrm{N} + (2.05 \times 10^{-24}\ \mathrm{N})(\cos 60^\circ)$$
$$= -1.25 \times 10^{-25}\ \mathrm{N}.$$

The sum of the $y$ components gives us

$$F_{1,\text{net},y} = F_{12,y} + F_{14,y} = 0 + F_{14}\sin 60^\circ$$
$$= (2.05 \times 10^{-24}\ \mathrm{N})(\sin 60^\circ)$$
$$= 1.78 \times 10^{-24}\ \mathrm{N}.$$

The net force $\vec{F}_{1,\text{net}}$ has the magnitude

$$F_{1,\text{net}} = \sqrt{F^2_{1,\text{net},x} + F^2_{1,\text{net},y}} = 1.78 \times 10^{-24}\ \mathrm{N}. \qquad \text{(Answer)}$$

To find the direction of $\vec{F}_{1,\text{net}}$, we take

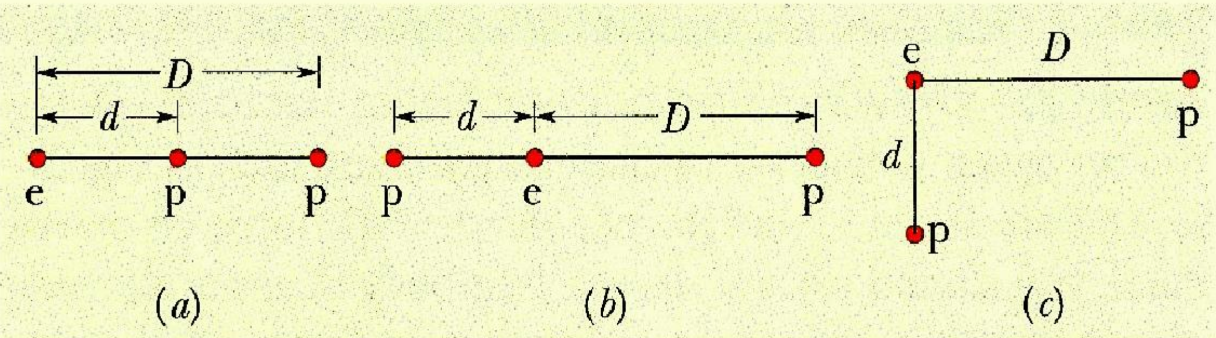
$$\theta = \tan^{-1}\frac{F_{1,\text{net},y}}{F_{1,\text{net},x}} = -86.0^\circ.$$

However, this is an unreasonable result because $\vec{F}_{1,\text{net}}$ must have a direction between the directions of $\vec{F}_{12}$ and $\vec{F}_{14}$. To correct $\theta$, we add 180°, obtaining

$$-86.0^\circ + 180^\circ = 94.0^\circ. \qquad \text{(Answer)}$$

# Coulomb's Law

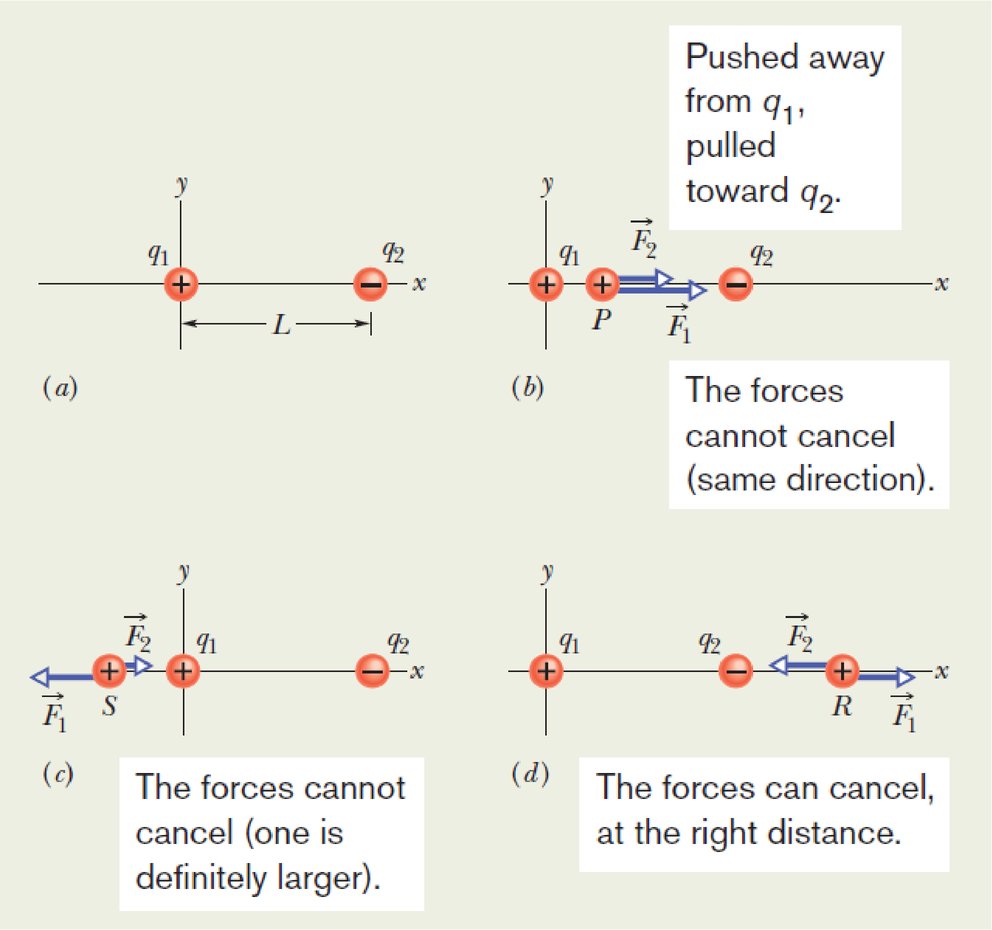
**CHECKPOINT 3** The figure here shows three arrangements of an electron e and two protons p. (a) Rank the arrangements according to the magnitude of the net electrostatic force on the electron due to the protons, largest first. (b) In situation *c*, is the angle between the net force on the electron and the line labeled *d* less than or more than 45°?



# Coulomb's Law

Figure 21-9*a* shows two particles fixed in place: a particle of charge $q_1 = +8q$ at the origin and a particle of charge $q_2 = -2q$ at $x = L$. At what point (other than infinitely far away) can a proton be placed so that it is in *equilibrium* (the net force on it is zero)? Is that equilibrium *stable* or *unstable*? (That is, if the proton is displaced, do the forces drive it back to the point of equilibrium or drive it farther away?)

# Coulomb's Law




$$\frac{1}{4\pi\varepsilon_0}\frac{8qq_p}{x^2} = \frac{1}{4\pi\varepsilon_0}\frac{2qq_p}{(x-L)^2}.$$

$$\left(\frac{x-L}{x}\right)^2 = \frac{1}{4}.$$

$$\frac{x-L}{x} = \frac{1}{2},$$

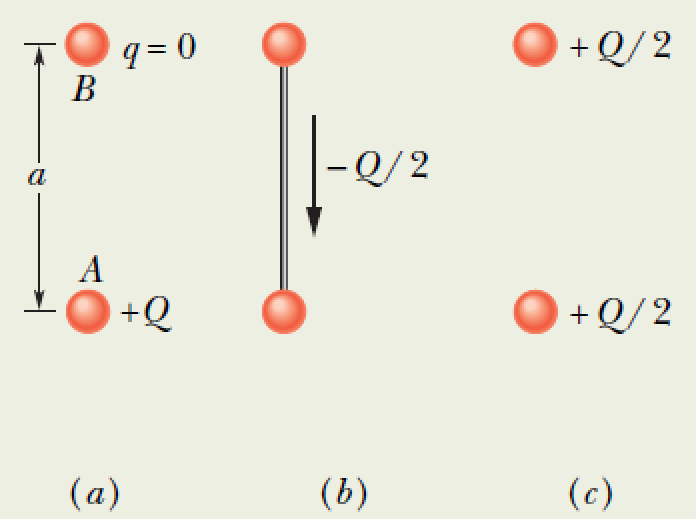
$$x = 2L.$$

The equilibrium at x=2Lis unstable; that is, if the proton is displaced leftward from point *R*, then $F_1$ *and* $F_2$ both increase but $F_2$ increases more (because $q_2$ is closer than $q_1$), and a net force will drive the proton farther leftward. If the proton is displaced rightward, both $F_1$ and $F_2$ decrease but $F_2$ decreases more, and a net force will then drive the proton farther rightward. In a stable equilibrium, if the proton is displaced slightly, it returns to the equilibrium position.

# Coulomb's Law

In Fig. 21-10*a*, two identical, electrically isolated conducting spheres *A* and *B* are separated by a (center-to-center) distance *a* that is large compared to the spheres. Sphere *A* has a positive charge of $+Q$, and sphere *B* is electrically neutral. Initially, there is no electrostatic force between the spheres. (Assume that there is no induced charge on the spheres because of their large separation.)

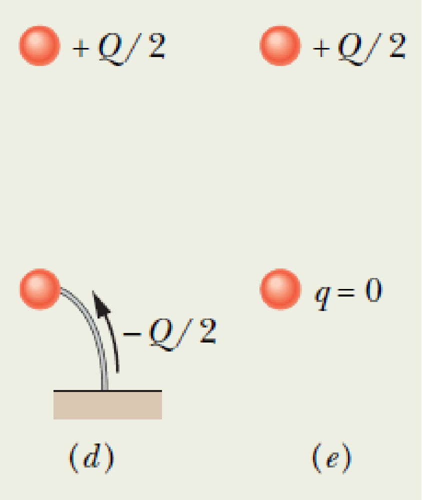
(a) Suppose the spheres are connected for a moment by a conducting wire. The wire is thin enough so that any net charge on it is negligible. What is the electrostatic force between the spheres after the wire is removed?




$$F = \frac{1}{4\pi\varepsilon_0}\frac{(Q/2)(Q/2)}{a^2} = \frac{1}{16\pi\varepsilon_0}\left(\frac{Q}{a}\right)^2.$$

# Coulomb's Law

(b) Next, suppose sphere $A$ is grounded momentarily, and then the ground connection is removed. What now is the electrostatic force between the spheres?



# Coulomb's Law

**CHECKPOINT 4** Initially, sphere $A$ has a charge of $-50e$ and sphere $B$ has a charge of $+20e$. The spheres are made of conducting material and are identical in size. If the spheres then touch, what is the resulting charge on sphere $A$?

# Coulomb's Law

The nucleus in an iron atom has a radius of about $4.0 \times 10^{-15}$ m and contains 26 protons.

(a) What is the magnitude of the repulsive electrostatic force between two of the protons that are separated by $4.0 \times 10^{-15}$ m?

(b) What is the magnitude of the gravitational force between those same two protons?

# Coulomb's Law

The nucleus in an iron atom has a radius of about $4.0 \times 10^{-15}$ m and contains 26 protons.

(a) What is the magnitude of the repulsive electrostatic force between two of the protons that are separated by $4.0 \times 10^{-15}$ m?

**KEY IDEA**

The protons can be treated as charged particles, so the magnitude of the electrostatic force on one from the other is given by Coulomb's law.

***Calculation:*** Table 21-1 tells us that the charge of a proton is $+e$. Thus, Eq. 21-4 gives us

$$F = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}$$

$$= \frac{(8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(1.602 \times 10^{-19} \text{ C})^2}{(4.0 \times 10^{-15} \text{ m})^2}$$

$$= 14 \text{ N}. \qquad \text{(Answer)}$$

***No explosion:*** This is a small force to be acting on a macroscopic object like a cantaloupe, but an enormous force to be acting on a proton. Such forces should explode the nucleus of any element but hydrogen (which has only one proton in its nucleus). However, they don't, not even in nuclei with a great many protons. Therefore, there must be some enormous attractive force to counter this enormous repulsive electrostatic force.

(b) What is the magnitude of the gravitational force between those same two protons?

**KEY IDEA**

Because the protons are particles, the magnitude of the gravitational force on one from the other is given by Newton's equation for the gravitational force (Eq. 21-2).

***Calculation:*** With $m_p$ ($= 1.67 \times 10^{-27}$ kg) representing the mass of a proton, Eq. 21-2 gives us

$$F = G\frac{m_p^2}{r^2}$$

$$= \frac{(6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2)(1.67 \times 10^{-27} \text{ kg})^2}{(4.0 \times 10^{-15} \text{ m})^2}$$

$$= 1.2 \times 10^{-35} \text{ N}. \qquad \text{(Answer)}$$

# What have we learnt

- Properties of electric charge
  - Positive, negative, quantized, conserved
- Electrical properties of materials
  - Conductors, insulators, semiconductors, superconductors
  - Neutral, charged, grounded
- Coulomb’s law: Electrostatic Force
  - Principle of superposition, Shell theorem